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First Results from the DEAP-3600 Dark Matter Search with Argon at SNOLAB

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This Letter reports the first results of a direct dark matter search with the DEAP-3600 single-phase liquid argon (LAr) detector. The experiment was performed 2 km underground at SNOLAB (Sudbury, Canada) utilizing a large target mass, with the LAr target contained in a spherical acrylic vessel of 3600 kg capacity. The LAr is viewed by an array of PMTs, which would register scintillation light produced by rare nuclear recoil signals induced by dark matter particle scattering. An analysis of 4.44 live days (fiducial exposure of 9.87 ton day) of data taken during the initial filling phase demonstrates the best electronic recoil rejection using pulse-shape discrimination in argon, with leakage $<1.2 \times 10^{-7}$ (90% C.L.) between 15 and 31 keV_{ee}. No candidate signal events are observed, which results in the leading limit on weakly interacting massive particle (WIMP)-nucleon spin-independent cross section on argon, $<1.2 \times 10^{-44}$ cm² for a 100 GeV/*c*² WIMP mass (90% C.L.).

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It is well established from astronomical observations that dark matter (DM) constitutes most of the matter in the Universe [1], accounting for 26.8% of the energy density, compared to 4.9% for ordinary matter. Weakly interacting massive particles (WIMPs) are one of the leading DM candidates. The direct detection of WIMPs from the galactic halo is possible via elastic scattering, producing nuclear recoils (NR) of a few tens of keV.

This Letter reports on the first DM search from DEAP-3600, a liquid argon (LAr) detector which uses single-phase technology, registering only the primary scintillation light from the target medium. This is the first DM search result from a LAr detector, of any technology, exceeding a 1 ton target mass, and the first such result from a single-phase detector, of any target species, at this scale. We emphasize the importance of exceeding the ton scale: thus

far only one technology, the liquid Xe time projection chamber (TPC), has achieved a 1 ton fiducial mass, while a credible direct detection discovery of DM will require observation in multiple target species. Further, while the WIMP mass reach of collider experiments is limited by beam energy, direct detection experiments are limited only by total exposure, and so a large enough underground detector with sufficiently low backgrounds can access high WIMP mass regions not accessible to colliders. The DEAP-3600 single-phase design offers excellent scalability to kton-scale LAr detectors [2,3].

In this Letter, we report the best background rejection using pulse-shape discrimination (PSD) in argon at a low energy threshold, most relevant for WIMP searches. The PSD uses the substantial difference in LAr scintillation timing between NR and electronic recoils (ER) to reject the dominant β/γ backgrounds [4,5] at the 10^{-7} level, 4 orders of magnitude beyond that achieved in LXe. This capability will enable a large underground detector using argon to reject the electron backgrounds from solar neutrinos and reach the neutrino floor defined by coherent scattering of atmospheric neutrinos. Employing this PSD, this Letter reports a background-free DM search in 9.87 ton day exposure, resulting in the best limit on the WIMP-nucleon cross section measured with argon, in the high WIMP mass regime, second only to Xe TPC-based searches.

The detector is comprised of an atmospheric LAr target contained in an acrylic vessel (AV) cryostat capable of storing 3600 kg of argon. The AV is viewed by 255 Hamamatsu R5912-HQE photomultiplier tubes (PMTs) detecting scintillation light from the target. The PMTs are coupled to the AV by 50 cm-long acrylic light guides (LGs). The inner AV surface was coated *in situ* with a 3 μm layer of wavelength shifter, 1,1,4,4-tetraphenyl-1,3-butadiene (TPB) to convert 128 nm Ar scintillation light into blue light transmitted through acrylic. The AV neck is wrapped with optical fibers read out by PMTs, to veto light emission in the AV neck region. The detector is housed in a stainless steel spherical shell immersed in an 8 m diameter ultrapure water tank. All detector materials were selected to achieve the background target of < 0.6 events in a 3 ton year [3]. To avoid $^{222}\text{Rn}/^{210}\text{Pb}$ contamination of the AV surface, the inner 0.5 mm layer of acrylic was removed *in situ* after construction; Rn exposure was then strictly limited.

PMT signals are decoupled from the high voltage by a set of custom analog signal-conditioning boards, digitized (CAEN V1720) and handled by MIDAS DAQ [6].

The PMT charge response functions are calibrated daily with a system of 22 pulsed-LED-driven fibers injecting 435 nm light [3]. A PMT charge response model is used to calculate the mean single photoelectron (SPE) charges, $\hat{\mu}_{\text{SPE}}$, with the combined 3% statistical and systematic uncertainty [7]. A Monte Carlo model of the detector, using the GEANT4-based RAT [8], includes a full PMT signal

simulation based on *in situ* measured time vs charge distributions for noise sources: late, double, and after-pulsing (AP) for each PMT [3,7,9].

The charge of each identified pulse is divided by the PMT-specific $\hat{\mu}_{\text{SPE}}$ to extract the number of photoelectrons (PEs). F_{prompt} is defined for each event as the ratio of prompt to total charge, $F_{\text{prompt}} \equiv [(\sum_{\{i|t_i \in (-28\text{ ns}, 150\text{ ns})\}} Q_i) / (\sum_{\{i|t_i \in (-28\text{ ns}, 10\text{ }\mu\text{s})\}} Q_i)]$, where Q_i is the pulse charge in PE and t_i is the pulse time relative to the event time. The relative timing of each channel is calibrated with a fast laser source; the resulting overall time resolution is 1.0 ns. F_{prompt} is a powerful discriminator because it is sensitive to the ratio of excited singlet to triplet states in LAr, I_1/I_3 , with lifetimes of 6 and 1300 ns [10], respectively. This ratio is significantly different for ER and NRs.

The detector trigger was designed to accept all low-energy events above threshold, all high- F_{prompt} NRs and to cope with approximately 1 Bq/kg ^{39}Ar activity of LAr [11]. The PMTs signal is continuously integrated in windows 177 ns and 3100 ns wide, from which the prompt energy (E_{trigger}) and ratio of prompt and wide energies are calculated. All NR-like triggers with $E_{\text{trigger}} > 40$ PE, but only 1% of ^{39}Ar -decay-like triggers, are digitized; summary information is recorded for all events. For NR-like events above the analysis PE threshold, the trigger efficiency in the experiment live time is measured to be $(100^{+0.0}_{-0.1})\%$, by running in a very low threshold mode and after low-level cuts removing pileup (Table S1 in Supplemental Material [12]). For ER-like events, the measured trigger efficiency is $< 100\%$ below 120 PE because of their lower prompt charge.

Stability of the LAr triplet lifetime, τ_3 , was verified with a fit accounting for dark noise, TPB fluorescence [13], and PMT AP. From this fit $\tau_3 = 1399 \pm 20(\text{PMT syst}) \pm 8(\text{fit syst}) \pm 6(\text{TPB syst}) \pm 7(\text{AP syst})$ ns, where errors are evaluated by performing the fit separately on individual PMTs, varying the fit range, and varying the TPB fluorescence decay time and times of the AP distributions within uncertainties. This result is stable throughout the analyzed data set (Fig. S1 in the Supplemental Material [12]), and consistent with the literature value of 1300 ± 60 ns [10].

^{39}Ar β decay, the dominant source of scintillation events, results in low- F_{prompt} ERs. In order to define an F_{prompt} cut constraining the leakage of ^{39}Ar events into the NR band, the F_{prompt} distribution of ERs and its energy dependence were fitted with an 11-parameter empirical model of F_{prompt} vs PE, based on a widened Gamma distribution, $\text{PSD}(n, f) = \Gamma(f; \tilde{f}(n), b(n)) \otimes \text{Gauss}(f; \sigma(n))$, where $b(n) = a_0 + (a_1/n) + (a_2/n^2)$, $\sigma(n) = a_3 + (a_4/n) + (a_5/n^2)$ and $\tilde{f}(n)$ is parametrized as $a_6 + [a_7/(n - a_8)] + [a_9/(n - a_{10})^2]$. The two-dimensional fit of the model to the data (80–260 PE) has χ^2_{ndf} of 5581/(5236-11). Each PE bin contributes approximately equally to χ^2 ; as an example, a one-dimensional slice at 80 PE is shown in Fig. 1(a).

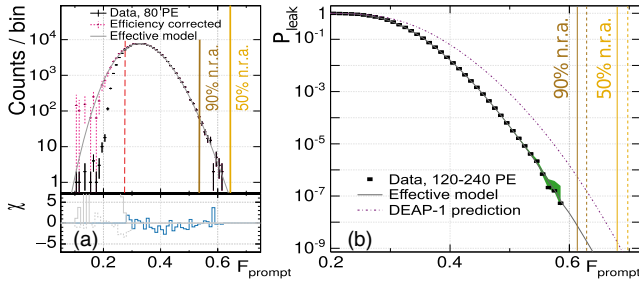


FIG. 1. (a) F_{prompt} vs PE distribution slice at 80 PE, with and without the trigger efficiency correction, is shown together with the effective model fit (performed above the red dashed line, indicating the F_{prompt} value below which the trigger efficiency is $<100\%$). The brown and orange lines correspond to 90% and 50% NRA. (b) Data and model for the 120–240 PE range with 1.87972×10^7 events, represented as leakage probability above given F_{prompt} . A conservative projection from DEAP-1 [5] is also shown with its NRA lines (dashed).

The PSD leakage measured in the 120–240 PE window with a 90% NR acceptance (NRA) is shown in Fig. 1(b). The extrapolated leakage is approximately $10\times$ lower than projected in the DEAP-3600 design [5]. As further PSD leakage reduction is expected from SPE counting [14], the original goal of a 120 PE analysis threshold in 3 ton years will likely be surpassed.

The energy calibration uses internal backgrounds and external radioactive sources. The internal calibration uses β 's from ^{39}Ar decay, with an end point of 565 keV and uniformly distributed in the detector (as WIMP-induced NRs would be). The external calibration uses a ^{22}Na source, which produces 1.27 MeV γ 's and a 30–50 keV photo-absorption feature near the AV surface. The simulated spectra of ^{39}Ar and ^{22}Na are fit to the data (separately, because of different spatial distributions) to find the energy response function relating T_{eff} [keV $_{ee}$] (electron-equivalent energy) to detected PE,

$$N_{\text{PE}}(T_{\text{eff}}) = c_0 + c_1 T_{\text{eff}} + c_2 T_{\text{eff}}^2, \quad (1)$$

where $c_0 = 1.2 \pm 0.2$ PE, $c_1 = 7.68 \pm 0.16$ PE keV $_{ee}^{-2}$, and $c_2 = -(0.51 \pm 2.0) \times 10^{-3}$ PE keV $_{ee}^{-2}$. The offset c_0 is fixed to values returned by analysis of the mean pretrigger window charge for each run. The ^{39}Ar fit result constitutes the nominal calibration, while the ^{39}Ar – ^{22}Na fit parameter differences, determined from a pair of runs taken just after the 2nd fill, are combined with the statistical uncertainties and used as systematic uncertainties from position and model dependence on $c_{1,2}$.

The final response function is shown in Fig. 2, together with the ^{39}Ar data, spanning from below to above the analysis energy window (see Fig. S2 in Supplemental Material [12] for the ^{22}Na fit). The energy response function linear terms, c_1 , for ^{39}Ar and ^{22}Na agree within errors.

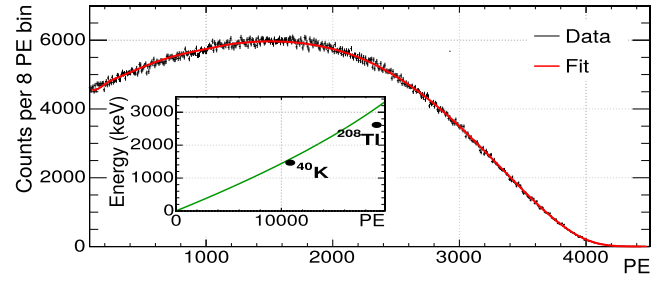


FIG. 2. Measured, trigger-efficiency-corrected ^{39}Ar β spectrum from a subset of data and the fit function (red) based on simulation, with $\chi^2_{\text{ndf}} = 1.02$. The inset shows the energy response function, Eq. (1), from the ^{39}Ar fit, and, as a cross-check, γ lines from ^{40}K and ^{208}Tl . ^{208}Tl diverges from the function because of PMT and DAQ nonlinearity.

The response function is extrapolated to compare with high-energy γ lines, see Fig. 2.

The light yield (LY) at 80 PE is 7.80 ± 0.21 (fit syst) ± 0.22 (SPE syst) PE/keV $_{ee}$, where the latter uncertainty is from SPE calibration.

A Gaussian resolution function is used in the fit, with $\sigma^2 = c_0 + p_1(\text{PE} - c_0)$. The resolution at 80 PE extrapolated from best fit values for ^{39}Ar and ^{22}Na is $20 \pm 1\%$ and $21 \pm 1\%$, respectively. A lower bound on the energy resolution at 80 PE is 12% ($p_1 = 1.185$), determined from counting statistics widened by the measured *in situ* SPE charge resolution. Because of the steeply falling WIMP-induced spectrum, broader resolutions imply stronger limits at low WIMP masses. Thus, using this lower bound is conservative.

NRA of the F_{prompt} cut is determined from a simulation of ^{40}Ar recoils distributed uniformly in LAr. The simulation assumes the quenching factor (QF, the LY of NRs relative to ERs) measured by SCENE [15] at zero electric field, and the I_1/I_3 energy dependence required to reproduce the reported median \mathcal{F}_{90} values; SCENE uncertainties are propagated through the analysis. The simulation applies the full response of the detection and analysis chain, including all noise components affecting the F_{prompt} distribution shape and width. PMT AP is the dominant effect contributing to shifting F_{prompt} relative to the intrinsic value [9], with an average AP probability of $(7.6 \pm 1.9)\%$ [3], $\sim 5\times$ larger than in SCENE. This 7.6% produces a proportional 5% shift in the median F_{prompt} . A comparison of external neutron AmBe source data with a simplified detector simulation shows qualitative agreement and serves as a validation (Fig. S3 in Supplemental Material [12]). AmBe data are not used directly to model the WIMP-induced NRA as 59% of AmBe events in the 120–240 PE window contain multiple elastic neutron scatters.

The region-of-interest (ROI), see Fig. 3, was defined by allowing for an expectation of 0.2 leakage events from the ^{39}Ar band, determined with the PSD model. The smaller number of ^{39}Ar events in the short exposure and the low

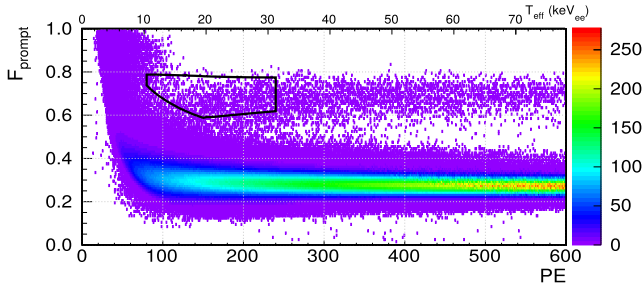


FIG. 3. AmBe source data after cuts, with the WIMP search ROI (black box).

F_{prompt} leakage allowed us to set the threshold at 80 PE (10 keV_{ee}), lower than the nominal 120 PE originally projected [5]. Above 150 PE, the lower limit on F_{prompt} is chosen to remove 5% of NRs in each bin. The ROI also has a maximum F_{prompt} chosen to remove 1% of NRs in each bin. The maximum energy of 240 PE, where the nominal design value was used (subject to future optimization), reduces possible backgrounds from the surface α activity [16].

The first LAr fill took approximately 100 days between May and mid-August 2016. For the majority of this time, Ar gas was introduced into the detector from the purification system for cooling. In the final phase of the fill, shortly following the discussed data set, a leak in the detector neck contaminated LAr with clean Rn-scrubbed N_2 . The detector was subsequently emptied and refilled, and it has been taking data since Nov. 1, 2016, with a slightly lower liquid level.

Here, we focus on Aug. 5–15 (9.09 days), when the detector contained a constant LAr mass. A sharp drop in rate between PMTs facing the liquid vs the vapor space, permits determination of the fill level, $590 \pm 50 \text{ mm}$ above the AV center, and the full LAr mass: $3322 \pm 110 \text{ kg}$ (Fig. S1 in the Supplemental Material [12]).

Calibrations were performed after the 2nd fill: 23 h of ^{22}Na (Nov. 3–4) and 65 h of AmBe data (Dec. 2–4).

Data were analyzed from runs where (1) the difference between the maximum and minimum AV pressures corresponded to $< 10 \text{ mm}$ change in the liquid level and (2) there were no intermittently misbehaving PMTs, i.e., no PMT read $< 50\%$ of its average charge, determined from approximately 5 minute samples. Independently, during this data set, one PMT was turned off (and has since returned to operation). In all cases, pressure excursions were correlated with periods of the cryocoolers operating at reduced power. Out of 8.55 d of physics runs, 2.92 d are removed by failing both criteria and 0.91 d by failing criterion 2 alone. The remaining 4.72 d contained a total dead time of 0.28 d, due to $17.5 \mu\text{s}$ dead time after each trigger, resulting in a 4.44 d live time.

Acceptance for WIMP-induced NR events [Fig. 4(a)] is determined using a combination of (uniformly distributed)

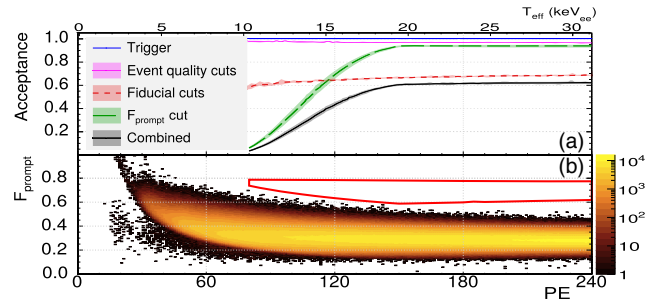


FIG. 4. (a) The acceptance in the 80–240 PE window, with systematic errors (maximum variation about the weighted mean, run-by-run). Uncertainties on trigger acceptance and F_{prompt} cut acceptance are discussed in the text. (b) F_{prompt} vs PE for events passing cuts, with the WIMP search ROI (red).

^{39}Ar events and simulation of the F_{prompt} for NRs. The sample of ^{39}Ar single-recoils is obtained first by applying low-level cuts to remove events (1) from DAQ calibration, (2) from pile-up, or (3) highly asymmetric ($> 40\%$ of charge in a single PMT), e.g. Cherenkov events in LGs and PMTs. The approach of measuring acceptance for NRs using ERs is used since none of the cut variables depend on the pulse time information, only F_{prompt} does, which is handled separately. The F_{prompt} simulation for NRs is validated by comparison with the AmBe data. See Table S1 in the Supplemental Material [12] for the impact breakdown of run selection and cuts.

Quality cuts are applied to ^{39}Ar events within the energy window in order to determine the ER acceptance: the event time cut requires the scintillation peak positioned early in the waveform (for reliable F_{prompt} evaluation), cuts on the fraction of charge in the brightest PMT and on the neck veto remove high-charge AP triggering the detector as well as light emission in the AV neck (e.g. Cherenkov). We have identified a class of background events originating in the neck region and are characterizing it for future larger-exposure searches.

The fiducial acceptance is determined relative to the events remaining after the quality cuts. Fiducialization employs low-level PE ratio cuts. These are that the fraction of scintillation-induced (AP corrected) PE [9,14] in the PMT that detects the most light be $< 7\%$, and that the fraction of charge in the top 2 PMT rows be $< 5\%$. These variables are strongly correlated with the radial and vertical event positions, respectively, and so they can reject events at the surface of the detector and in the neck. The volume, after cuts on these variables (Table S1 in the Supplemental Material [12]), corresponds roughly to a sphere of radius $\sim 773 \text{ mm}$, truncated at the LAr level ($z \approx 590 \text{ mm}$). The fiducial mass, $2223 \pm 74 \text{ kg}$, is determined from the full LAr mass and the measured acceptance of the fiducialization cuts. The expected ^{39}Ar activity contained therein is $2245 \pm 198 \text{ Bq}$ [11], consistent with the fiducial rate observed, $2239 \pm 8 \text{ Hz}$.

Position reconstruction algorithms in this analysis were used only as a cross check (Fig. S4 in the Supplemental Material [12]).

The main background sources are α activity, neutrons, and leakage from ^{39}Ar and other ERs. As external backgrounds contributions to this early analysis are negligible, we have not yet determined their distributions.

^{222}Rn , ^{218}Po , and ^{214}Po α decays are identified in the LAr bulk as high-energy peaks or based on delayed coincidences, α - α (^{222}Rn - ^{218}Po and ^{220}Rn - ^{216}Po) or β - α (^{214}Bi - ^{214}Po), resulting in activities: $(1.8 \pm 0.2) \times 10^{-1} \mu\text{Bq/kg}$ of ^{222}Rn , $(2.0 \pm 0.2) \times 10^{-1} \mu\text{Bq/kg}$ of ^{214}Po , and $(2.6 \pm 1.5) \times 10^{-3} \mu\text{Bq/kg}$ of ^{220}Rn (Fig. S5 in the Supplemental Material [12]). For comparison, approximate values from other experiments are $66 \mu\text{Hz/kg}$ of ^{222}Rn and $10 \mu\text{Hz/kg}$ of ^{220}Rn in LUX [17], $6.57 \mu\text{Bq/kg}$ of ^{222}Rn and $0.41 \mu\text{Bq/kg}$ of ^{220}Rn in PandaX-II [18], and $10 \mu\text{Bq/kg}$ of ^{222}Rn in XENON1T [19]. The out-of-equilibrium ^{210}Po activity is determined with a fit of simulated spectra to the data: $0.22 \pm 0.04 \text{ mBq/m}^2$ on the AV surface and $<3.3 \text{ mBq}$ in the AV bulk (Fig. S6 in the Supplemental Material [12]).

(α, n) reactions and spontaneous fission in the PMTs is the expected dominant source of neutron events. It is constrained with measurements of the 2614 keV and 1764 keV γ -rays from the ^{232}Th and ^{238}U decay chains, respectively. *In situ* activities of both decay chains agree within a factor of two with a simulation based on the screening results. Neutron backgrounds are also constrained by searching for NRs followed by capture γ 's, with efficiency calibrated using neutrons from an AmBe source deployed near the PMTs. No neutron candidates were seen in 4.44 d (80–10000 PE, no fiducial cuts), which is consistent with the assay-based expectation.

Systematic uncertainties in the WIMP cross section limit include uncertainties in the NR energy response, total exposure, and cut acceptance [see Fig. 4(a)]. The F_{prompt} cut acceptance uncertainty is determined from uncertainties in the simulation parameters, including I_1/I_3 (derived from the SCENE \mathcal{E}_{90} measurements [15]), τ_3 ($\pm 70 \text{ ns}$, from the difference between SCENE and this work), and the AP probability. The main uncertainty is from the NR energy response. This is dominated by uncertainties in Eq. (1), followed by uncertainties in the NR QF. SCENE reports two energy-dependent NR QFs that differ due to nonunitary recombination at a null field: $\mathcal{L}_{\text{eff},^{83\text{m}}\text{Kr}}$ (the NR LY relative to that from a $^{83\text{m}}\text{Kr}$ ER calibration) and \mathcal{L} (the Lindhard-Birks QF describing the suppression of photon and ionized electron production) We varied the Lindhard-Birks QF fit to \mathcal{L} to account for the uncertainty of normalizing NR LY relative to the ^{39}Ar spectrum, rather than to $^{83\text{m}}\text{Kr}$ calibration, as SCENE did, using the NEST model [20], fitting Thomas-Imel and Doke-Birks recombination parameters to SCENE's $\mathcal{L}_{\text{eff},^{83\text{m}}\text{Kr}}$ values. These factors, along with the

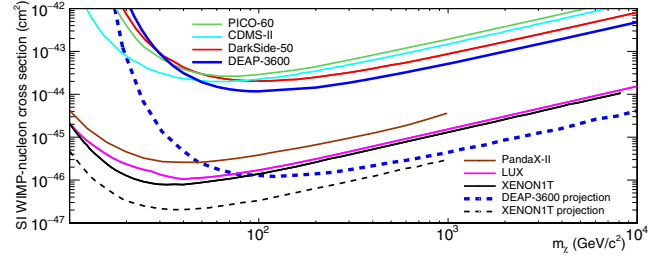


FIG. 5. Spin-independent WIMP-nucleon cross section 90% C.L. exclusion from 4.44 live days of DEAP-3600 data. Also shown are current results from other searches [23–28], and projections for XENON1T and DEAP-3600 (a 3 ton year background-free exposure with a 15 keV_{ee} threshold).

uncertainty in Birks' constant reported by SCENE and the difference between \mathcal{L} and $\mathcal{L}_{\text{eff},^{83\text{m}}\text{Kr}}$ were included in the overall QF uncertainty.

No events are observed in the ROI, see Fig. 4(b). Figure 5 shows the resulting limit on the spin-independent WIMP-nucleon scattering cross section, based on the standard DM halo model [21]. The 90% C.L. upper limit is derived employing the Highland-Cousins method [22]. For a more conservative limit, the predicted ^{39}Ar leakage was not subtracted. This analysis was not blind.

DEAP-3600 achieved $7.8 \text{ PE/keV}_{ee} \text{ LY}$ at the end of the detector fill without recirculation, and it demonstrated better-than-expected PSD (permitting a 37 keV_r threshold), with promising α and neutron background levels. Analysis of the first 4.44 d of data results in the best limit at low energies on discrimination of β -decay backgrounds using PSD in LAr at 90% NRA, with measured leakage probability of $<1.2 \times 10^{-7}$ (90% C.L.) in the energy window $15\text{--}31 \text{ keV}_{ee}$ ($52\text{--}105 \text{ keV}_r$). This measurement has a lower threshold than DEAP-1 [5] and higher statistics than DarkSide-50 [26]. After NR selection cuts, no events are observed, resulting in the best spin-independent WIMP-nucleon cross section limit measured in LAr of $<1.2 \times 10^{-44} \text{ cm}^2$ for a $100 \text{ GeV}/c^2$ WIMP (90% C.L.) (Recently, DarkSide-50 announced new results [29]; DEAP-3600 remains the most sensitive non-Xe search in the $48\text{--}90 \text{ GeV}/c^2$ mass range). Data collection has been ongoing since Nov. 2016 and forms the basis for a more sensitive DM search currently in progress.

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